21st Transducer Workshop
Vehicular Instrumentation/Transducer Committee

Blast Measurements: Selecting the Appropriate Pressure Transducer and Properly Interfacing It

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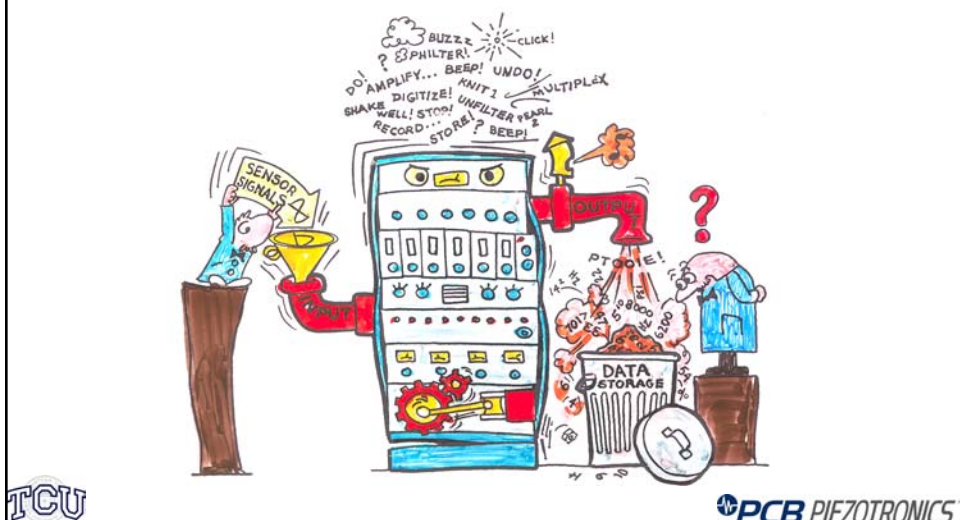*Fort Worth, TX 76129*

Presentation Goals

- Briefly describe the blast environment.
  - Identify the measurement objectives.
- Describe the applicable pressure transducer technologies.
  - Present advantages/disadvantages of each.
  - Describe transducer configurations.
- Discuss data validation techniques.
- Discuss data signal transmission.

In short, we want to avoid:

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The Blast Environment

Explosions in Air

- Types:

  ➢ Freely expanding shocks in air

  ➢ Constrained shocks

    ▪ Shock tubes

    ▪ Other vessels

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Explosions Defined

- Explosion: A process by which a pressure wave of finite amplitude is generated in air by <u>a rapid release in energy.</u>

  ➢ Energy sources:
    ▪ chemical materials
    ▪ nuclear materials
    ▪ stored energy in gas (boilers, gas storage bottles, muzzle blast)
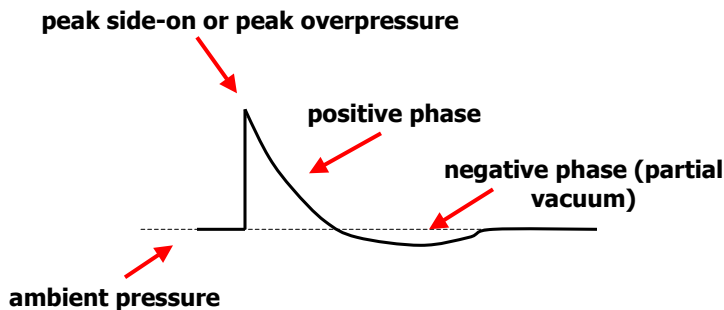   ▪ electrical gas (spark gap, vaporization of a wire/film)

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Focus: Freely Expanding Air Shocks (Nonlinear Process)

- The properties of air as a compressible gas cause the front of the disturbance to steepen as it passes through the air (i.e., "shocks up").

  - ➢ Discontinuities occur across the shock front in:
    - pressure
    - density
    - temperature

  - ➢ Shock front moves supersonically

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Ideal Pressure-time Response to an Explosion in a Still, Homogeneous Atmosphere

peak side-on or peak overpressure

positive phase

negative phase (partial vacuum)

ambient pressure

Net area is total impulse

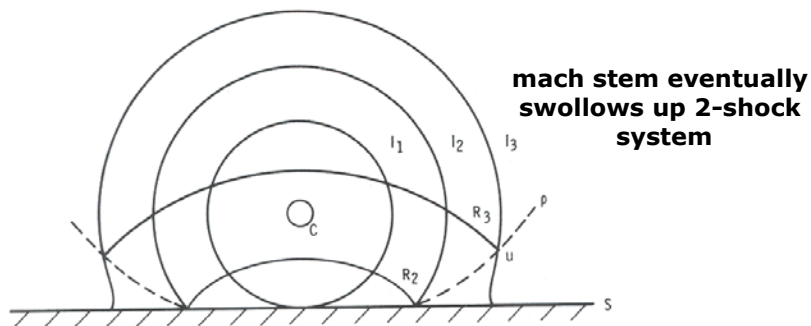TCU   *PCB PIEZOTRONICS*

Deviations From Ideal Responses Occur

- Causes:

  - ➤ reflections at contact surface between explosion products and air
  - ➤ low specific energy source may result in long travel distances before "shock up" occurs
  - ➤ caged explosives may result in fragments that temporarily outrun the blast wave
  - ➤ ground effects (dust, heat reflecting surfaces)
  - ➤ reflections from solid object or diffraction around it

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Reflections From a Rigid Wall

mach stem eventually swollows up 2-shock system

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Pressure Transducer Technologies for Blast

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How Blast Measurements Were Acquired in the 1960s

- Bulk-semiconductor, Wheatstone bridge, flush-diaphragm type pressure transducers (piezoresistive or PR)
  - e.g., Micro Systems, Schaevitz-Bytrex or Bytrex
  - ½"-20 external thread typical to 1000 psi
- Piezoelectric pressure transducers (operated into buried charge amplifiers) were used to enable low noise cable to be run.
  - Kistler, Atlantic Research
- Significant events 2nd part of 1960s:
  - ~1966 (integral electronics integrated into quartz transducers) (Kistler)
  - ~1969 (MEMS pressure transducers first used for blast measurements) (Kulite)

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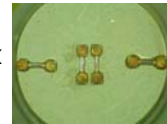
Historical Perspective:
(Late 1960s/Early 1970s)
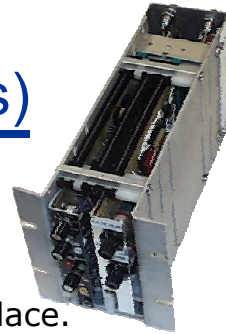
- Why were PR pressure transducers in favor?

  ➢ Signal conditioning was all ready in place.
  - Differential amplifiers/power supplies were required for existing strain gage circuits.
  ➢ Ease of static calibration (true dc response)
  ➢ MEMS (miniature electomechanical systems) transducers simply replaced existing PRs with no change required in signal conditioning.
  - resulted in smaller size, higher frequencies

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Historical Perspective:
## (Late 1960s/Early 1970s)

- Why was the market place slow to grasp quartz integral electronics transducers?

  ➢ Introducing electronics into the transducer in harsh environments was a new concept.
  - Transducer survivability was a customer concern.

  ➢ In addition, a new type signal conditioning was required.
  - Within Gov't Labs, signal conditioning, unlike transducers, was a capital expense item.
    - It had to be programmed into the budget cycle.

As a byproduct, MEMS (Kulite) captured a large part of the blast market place from acoustic levels through 20,000 psi. Endevco entered the market in the late 1970s, but never competed on cost. This situation is largely the same in 2004.

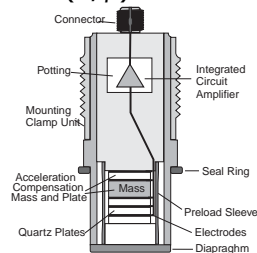TCU   PCB PIEZOTRONICS

Pros and Cons of PR/PE: Looking Back

- Thermal Effects: Transient temperatures to 1,000s of degrees will distort the transducer sensing diaphragm.

- MEMS:
  - require screens, grease, and/or RTVs for thermal delay
    - in ranges below 300 psi grease and/or RTV adds significant damping and reduces the transducer resonant frequency
    - screens are used to protect silicon diaphragms from particle impact
      - screens increase indicated pressure rise time

- Quartz:
  - Do not require screens.
 - Dynamic response unaffected by RTV or grease.

Mod. 113 .35 pC/psi
Accel. Comp.
High Frequency

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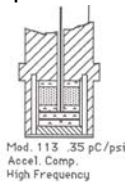
Pros and Cons of PR/PE: Looking Back

- Acceleration/Strain Response: Acceleration and resultant motion induced strain couple into trans-ducer sensing mechanism.

- MEMS:
  - Minimal influence due to material properties $(E/\rho)^{1/2}$ of silicon.

- Quartz:
  - Can be acceleration compensated.

Connector
Potting
Integrated Circuit Amplifier
Mounting Clamp Unit
Seal Ring
Acceleration Compensation Mass and Plate
Mass
Preload Sleeve
Quartz Plates
Electrodes
Diapraghm

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Pros and Cons of PR/PE: Looking Back

- Channel Continuity Checks: Enable verification of cable continuity.

- MEMS:
  - ➢ Shunting bridge enables step voltage through system but does not calibrate system due to thermal coefficient of resistance of bridge arms.

- Quartz:
  - ➢ Continuous continuity check via ICP® circuitry.
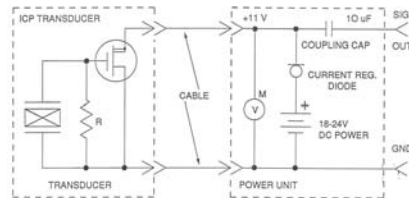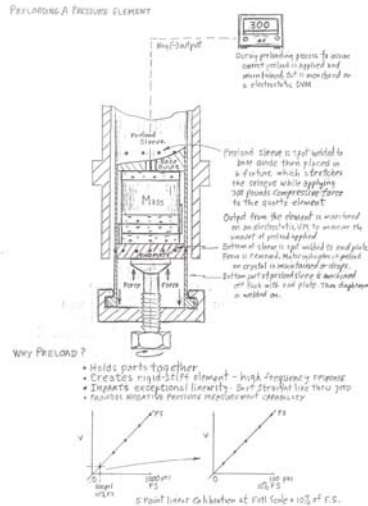

Pros and Cons of PR/PE: Looking Back

- Dynamic Range: Pressure range over which an acceptable signal/noise is achieved.

- MEMS:
  - ➢ 100 mV nominal FS
    - ▪ 0-500 psi transducer outputs 20 mV at 100 psi

- ICP Quartz:
  - ➢ 1000 mV typical FS
    - ▪ 0-500 psi transducer outputs 200 mV at 100 psi

Pros and Cons of PR/PE: Looking Back

- ICP Quartz:

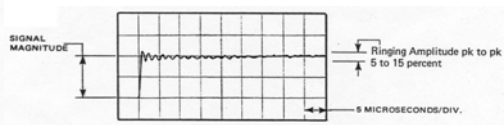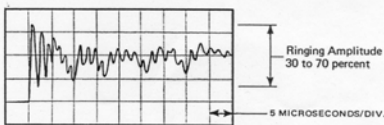# Pros and Cons of PR/PE: Looking Back

- Operating Pressure/Overrange Capability:

- MEMS:
  - 20,000 psi maximum range
  - 2-3 times over range without damage

- Quartz:
  - 200,000 psi maximum range
  - up to 200 times over range without damage

Pros and Cons of PR/PE: Looking Back

- Frequency Response:
  - ➢ High Frequency:
    - ▪ MEMS: 100 to 200 kHz at 100 psi
      ~1 MHz at 1,000 psi
    - ▪ Quartz: 400-500 kHz over above range
      - "Frequency tailoring" enhances overall response.

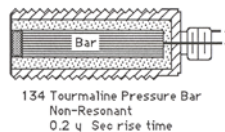

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Pros and Cons of PR/PE: Looking Back

- Frequency Response:
  - ➢ High Frequency:
    - ▪ PE: PCB Series 134 tourmaline pressure bar has no competition (non-resonant response).
      - However, recording capability is typically less than 1-2 msec.
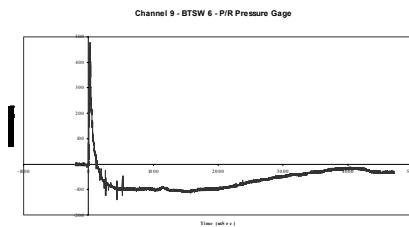   - o Thermal sensitivity of tourmaline.

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Pros and Cons of PR/PE: Looking Back

- Frequency Response:
  - ➢ Low Frequency:
    - ▪ MEMS pressure sensors have dc response.
      - • Ambient temperature changes influence the dc reference which ratio as % of full scale.

Channel 9 - BTSW 6 - P/R Pressure Gage

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Pros and Cons of PR/PE: Looking Back

- Frequency Response:
  - ➢ Low Frequency:
    - ▪ Quartz ICP®
      - • Time constants (τ) to 1000 seconds are available.
        - ✓ integration: (pulse duration) < $\tau/100$; less than 0.5% error
        - ✓ pulse peak: (pulse duration) < $\tau/100$; less than 1.0% error

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Pros and Cons of PR/PE: Summary

Attribute	PR	PE
• Thermal Effects		X
• Acceleration/Strain Response	X	X
• Cable/Continuity Checks	X	X
• Dynamic Range		X
• Operating Pressure/Over Range		X
• Frequency Response		
➢ High	X	X+
➢ Low	X	X
✓ *Dynamic range of PE along with increased durability should minimize inventory levels and associated costs.*		

X = best performance, (X   X) = equal performance
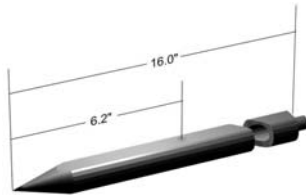
✓ *Key Point*

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Interfacing the Sensor

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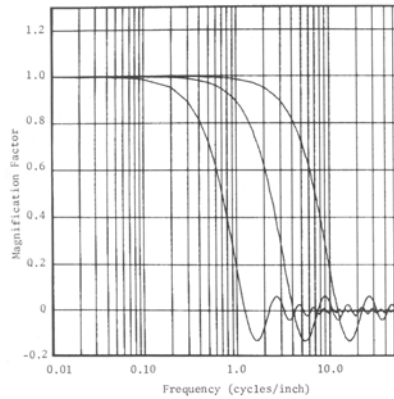# Probes for Side on Measurements

Pencil Probe

$$\lambda f = c$$

Spatial Averaging Frequency Response

Recesses Mounts Can Cause Problems

$$f_n = c/(4\pi)[\pi d^2/(V(L + .85d))]^{1/2}$$

In this equation, c is the velocity of sound of the gas being measured ($\cong$ 1100 feet/second for room-temperature air), V is the volume of the lower cavity, L is the length of the entrance tube, and d is the diameter of this tube.

$$f = [(2n-1)c]/4L \qquad (2)$$

where n = 1 corresponds to the first natural frequency; c and L have the same meaning as before.

It's been suggested that the Helmholtz resonator model (top) should transition to the wave equation model (bottom) when the volume of the tube is about one-half the volume of the chamber.
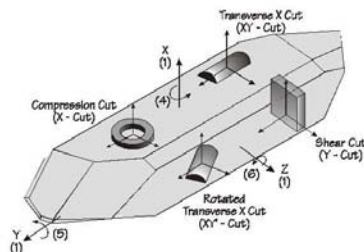
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Data Validation

Placebo Transducers

thermoelectric, photoelectric, electromagnetic, triboelectric, and other energy induced effects can result in additive electrical signals

$$P_{xx} = d_{11}\sigma_{xx} - d_{11}\sigma_{yy} + 0\,\sigma_{zz} + d_{14}\tau_{yz} + 0\,\tau_{zx} + 0\,\tau_{xy}$$
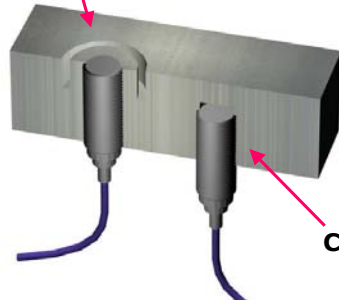
$$P_{yy} = 0\,\sigma_{xx} + 0\,\sigma_{yy} + 0\,\sigma_{zz} + 0\,\tau_{yz} - d_{14}\tau_{zx} - 2d_{11}\tau_{xy}$$

$$P_{zz} = 0\,\sigma_{xx} + 0\,\sigma_{yy} + 0\,\sigma_{zz} + 0\,\tau_{yz} + 0\,\tau_{zx} + 0\,\tau_{xy}$$

Check Channels

Solution

strain and/or acceleration checks

Check Channel

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Signal Transmission

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Signal Transmission

- ICP® Long Cable Considerations
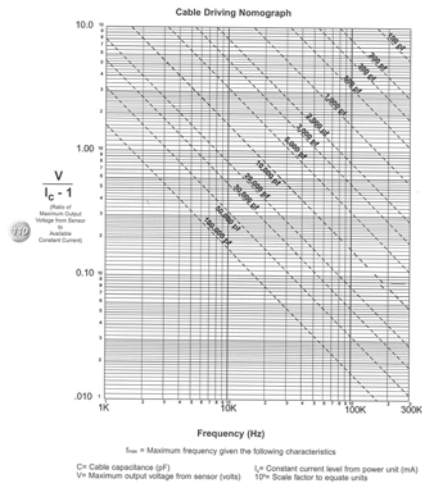
  $f_{max} = 10^9 / [2\pi CV/(l_c - 1)]$

  where, fmax = maximum frequency (Hertz)

  C = cable capacitance (picofarads)
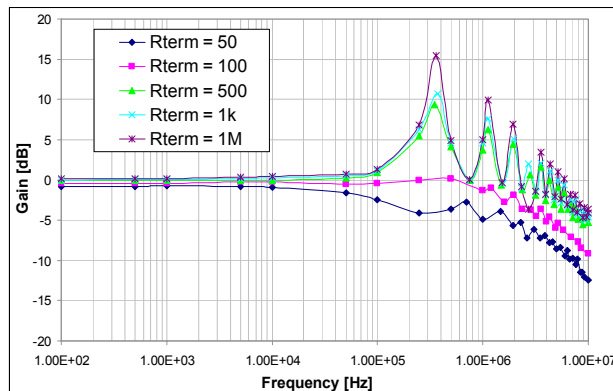
  V = maximum peak output from sensor (volts)

  lc = constant current from signal conditioner (mA)

  10^9 = scaling factor to equate units

Cable Driving Nomograph

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Signal Transmission

- MEMS: Long cables reflect high frequencies

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Presentation Conclusion

- Briefly describe the blast environment.
  - ➢ Identify the measurement objectives.
- Describe the applicable pressure transducer technologies.
  - ➢ Present advantages/disadvantages of each.
  - ➢ Describe transducer configurations.
- Discuss data validation techniques.
- Discuss data signal transmission.

Thanks

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